ELECTRICAL DISCHARGE DIAMOND GRINDING OF HIGH SPEED STEEL

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CERTIFICATE

It is certified that the thesis work entitled *Electrical Discharge Diamond Grinding o* *High Speed Steel* by MANOJ GUPTA has been carried out under my supervision, an that it has not been submitted elsewhere for a degree.

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DEDICATED

TO

MY PARENTS

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Abstract

The present thesis work is on new hybrid machining process called Electrical Discharge Diamond Grinding which integrates diamond grinding and electrical discharge machining (EDM) for machining electrically conducting hard materials. During the process the work piece is simultaneously subjected to heating by continuos ejection of electrical spark discharges bridging the metallic wheel bond and the work, and abrasion by diamond grains. It is cost effective and a relatively rapid machining technique that are particularly suited to advanced materials.

During grinding of hard materials, it is essential to frequently dress the wheel surface to maintain a wheel topography for effective grinding, due to acute wheel loading and glazing problems. In EDDG, on account of erosion of the wheel bond by the spark discharges, dressing and declogging of the wheel is in-process which saves the unproductive down-time spent on wheel dressing. Moreover, electro-discharge dressing is more efficient than mechanical methods because it doesn't involve shearing and consequent loss of abrasives. This apart, the spark discharges thermally soften the work material in grinding zone, and thus facilitate grinding and reduce the grinding forces.

As EDM grinding hybrid process is in its early stages of development relatively less literature is available on the above process. Sincere efforts are required to make this process into mature technology. This thesis makes an attempt in this direction. The work reported in this thesis comprises both experimental and theoretical components. The accent in the experimental work is on examining the role of electrical spark

discharges incorporated at the wheel-work interface in enhancing the grinding performance. Experiments have been conducted on High Speed Steel work pieces.

Die-sinking type spark erosion machine is used for conducting the experiments. The set-up consists of a grinding spindle assembly and drive, mounted on the ram of the EDM machine to rotate metal-bonded diamond wheel about an axis parallel to the machine table, for material removal in cut-off configuration. The downfeed of the rotating wheel is regulated automatically by the servo control of the EDM system such that the metallic wheel bond and the work surface are separated by a gap, the width of which depends on the local breakdown strength of the dielectric used, for a particular servo reference voltage. The electrical spark discharges that occur in the interelectrode gap thus thermally influence the work surface and the wheel, in the grinding zone, while those diamond grains with protrusion height greater than the interelectrode gap-width abrade the work. The role of spark discharges in augmenting the grinding performance is appraised in terms of the material removal rate (MRR) and the grinding forces, and is compared to grinding with no spark assist. The input parameters investigated are the current, voltage, pulse on-time and duty factor.

Nomenclature

A_p	projected area due to a protruding grain
A_p^c	projected area of contact of the abrasive
F_n	normal force
F_n^P	normal force corresponding to pulse power p
F_t	tangential force
g_w	interelectrode gap-width
d	uncut chip thickness
H	work-material hardness
k	thermal conductivity
p	pulse power
P_h	abrasive protrusion height
q	power flux
R_x	recorder pen deflection for F_n
R_y	recorder pen deflection for F_t
r	radius of abrasive grain
r_a	radius of spark channel
T_{on}	pulse on time
T	temperature
z	ordinate of abrasive grain centre
α	thermal diffusivity
A_ω	material removal parameter
f	fraction of pulse power expanded at the anode
ϕ	integral complementary error function

List of Figures

List of Tables

Contents

Chapter 1

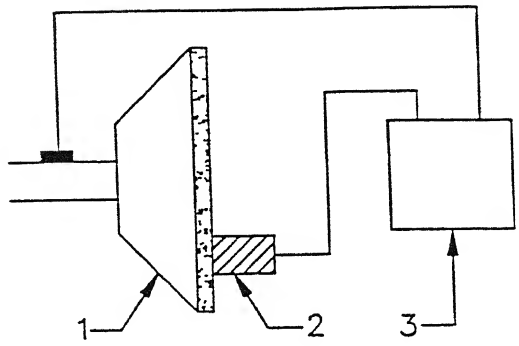
INTRODUCTION AND LITERATURE SURVEY

1.1 INTRODUCTION:

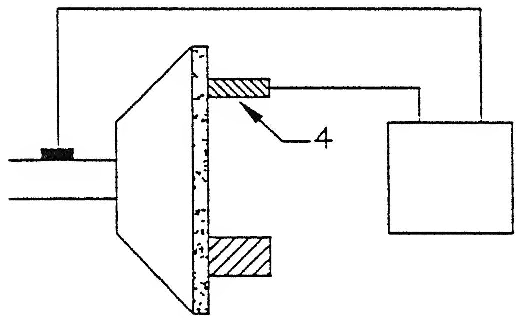
Hybrid process combines two or more machining techniques with a view to exploit their synergy to enhance productivity. Hybrid machining technology has a vital role in the machining of advanced materials. The work reported in this thesis is on a hybrid process called Electrical Discharge Diamond Grinding (EDDG) which integrates diamond grinding and electrical discharge machining (EDM) for machining electrically conducting hard-to-machine materials

Electrical discharge diamond grinding makes use of a metal bonded diamond grinding wheel . The work is simultaneously subjected to influence of electrical spark and diamond grains which results in surface melting as well as abrasion respectively. It is to be noted that this process is different from the electrical discharge grinding process, the terminology of which is a misnomer, as the rotating graphite electrode used therein for spark erosion is never in physical contact with the work, let alone abrade the work-material. Material removal in the electrical discharge diamond grinding process, in contrast to electrical discharge grinding, is predominantly by abrasion with the spark discharges playing more of supportive role.

There are two basic configurations by which the combination of grinding and electrical discharge machining is accomplished : (i) the workpiece itself acts as the



(a)



(b)

Figure 1.1 : Basic configuration of EDM-grinding hybrid process (a) Combined dressing and grinding zones (b) Isolated dressing and grinding zones (1-Wheel , 2-Work, 3-Power Supply, 4-Dressing electrode) [11].

dressing electrode whereby the grinding and wheel dressing zones are combined (fig 1.1a). The work material is thus located under the action of diamond grains and electrical spark discharges simultaneously which causes abrasion and material softening/removal respectively. The reduction of grinding forces and power, due to spark induced thermal softening of the work, and enhanced wheel performance due to continuous in-process dressing and declogging of wheel are the salient feature of this set up. Though the construction is simple, this arrangement precludes independent optimisation of grinding and dressing operations which in some cases might result in wasteful diamond wear. (ii) A separate electrode accomplishes electrodischarge dressing of the wheel outside the grinding zone (Fig. 1 1 b). The discharges are utilised for the renewal of the wheel topography alone and do not exert any influence on the work.. The wheel, however, can be dressed as and when the need arises, at an optimum rate, irrespective of the grinding conditions.

1.2 LITERATURE SURVEY:

One of the most well known hybrid machining process widely used in practice is "Electrochemical grinding (ECG)" for machining hard or fragile electrically conducting materials. Electrochemical grinding combines electrochemical machining and fine grinding processes. Electrochemical grinding systems closely resemble conventional grinding machines, grinding wheel with a conducting bond are utilised in ECG, with an electrolyte replacing the coolant. Machining proceeds with a potential applied across the wheel and work, with the wheel acting as the cathode. Typically,

90% of the material removal is by electrochemical dissolution and the rest by abrasion. Electrochemical grinding offers material removal rate upto 10 times of conventional grinding for material with hardness of 60 HRc or more. In case of homogeneous material like cemented carbides, the surface finish obtained is also better. Since the dimensional accuracy obtained in ECG is not as good as in conventional grinding, it is a normal practice to finish a component with no electrochemical material removal. The ECG is primarily applied in the manufacturing of carbide cutting tools, where saving in the order of 80% in wheel costs and 50% in labour costs have been reported [1], as compared to conventional grinding.

Electrochemical arc machining (ECAM) which combines electrochemical machining and spark erosion, relies on electrical discharge phenomenon in electrolytes for material removal [2]. The process of electrochemical machining involves injection of pulse voltage between a vibrating cathode tool and the workpiece, which are separated by a gap. During the course of vibration of the tool, in each cycle, as the interelectrode gap decreases, the current increases and sparking takes place by breakdown of the electrolyte. Material is removed by electrolysis when the gap-width and current are not conducive to sparking. Any metallurgical damage to the work due to spark discharges can also be removed by electrochemical action in this process. Here material removal rate is 50 to 100 times of that of electrical discharge machining, and 3 times that of electrochemical machining in hole-drilling process.

Low material removal rate is the primary limitation of ultrasonic machining (USM) process. The introduction of electrical discharge in the machining zone of USM has overcome this constraint to a large extent. For tungsten carbide materials, for example, a 50 to 85 % increase in MRR has been observed [3] on combining USM and EDM, due to activation of the abrasive slurry by the discharges. Scanning electron microscopic studies of the machined surfaces has indicated that abrasion effectively removes material which is thermally softened by the electrical discharges.

T. Uematsu [4] reports a hybrid process which involves combination of grinding, ultrasonic machining and electrical discharge machining for processing ceramic components. While grinding various ceramics imparting an ultrasonic vibration alone to the grinding wheel, results in decreasing the grinding force upto about 30 % of that in conventional grinding. Grinding of vary hard material like TiB_2 requires the addition of EDM in the process to obtain constant and low grinding forces and to maintain the grinding ability of the wheel during the course of machining.

The evolution of difficult -to-machine materials has given rise to a renewed interest in hot machining processes. In hot machining the work material is kept soft with respect to the tool with the help of some external heat source, which is expected to results in lower cutting forces, a better surface finish, and a longer tool life. Either plasma arc or laser beams are used as heat sources. Laser beams are however preferred to plasma arcs since they possesses a higher power density and strong directionality, moreover they are easy to handle.

Plasma hot machining of ceramic material is reported by Kitagawa and Maekawa [5]. The response to plasma arc heating of the work while machining has been found to be material dependent, while silicon nitride exhibited a marked decrease in turning forces as the work piece was heated to temperature above 1050^0 C, The forces were observed to be increased with a rise in workpiece temperature in case of alumina. The mechanism of chip formation for a variety of materials like mullite and silicon carbide, on heating, has been observed to change over from brittle fracture to plastic flow. A remarkable decrease in tool wear by a factor of eight, has been obtained by plasma hot machining of silicon nitride with a diamond tool.

In laser-assisted machining of hard materials, the beam intensity and interaction time are selected such that , during the cutting operation the workpiece is selectively heated to a defined depth which would reduce the cutting forces but cause no thermal damage to the functional surface generated. The resulting low cutting forces permit the machining of fragile or slender components. Milling of a cobalt-based alloy (stellite) with laser using a cubic boron nitride tool has been reported [6] to result in 70% reduction of cutting forces and 90% increase in tool life. Recently, laser-assisted grinding of hot-pressed silicon nitride has been found to increase the rate of material removal by six times with no mechanical damage imparted to the workpiece [7].

Research on chemical means of assisting material removal process is also being pursued. Interactions between chemical compounds added to the cutting fluid, and the work-surface, could influence the coefficient of friction in the cutting zone, the wear

of abrasives and the mechanical properties of the work material. The addition of boric acid while drilling polycrystalline alumina with a diamond core drill, for example, has been observed [8] to increase the MRR two folds due to boric acid influencing the grain boundary phase in alumina, promoting inter-granular fracture.

Publications available on EDM-grinding hybrid machining process are limited. References [9-11] on this process are more of an exploratory nature . An extensive literature survey yielded very few references that report a systematic study of the EDDG process, the salient results of which are reviewed in the following.

The role of electrical discharge introduced in the grinding zone while grooving and cutting-off of cemented carbides and a few advanced ceramics has been studied by Aoyama and Inasaki [12]. The responses investigated to evaluate the grinding performance were the grinding forces , wheel wear , surface finish, and the geometrical accuracy. Their set-up consisted of a surface grinding machine , with the wheel and the work electrically insulated from the rest of the machine, across which a pulsed D.C. voltage was applied for the spark discharges to occur in the grinding zone. With an increase in the applied voltage, the normal and tangential components of grinding forces were found to decrease at the expense of an increase in wheel wear. While the straightness of the ground groove improved with increasing voltage, due to reduced elastic deformation of the wheel associated with lower grinding forces, the surface finish was found to deteriorate. The electrical discharge have also been found to obviate the problem of chipping of ground edges , which is common while grinding

brittle materials. The decrease in the grinding forces has been attributed to two factors: (i) a portion of the material being removed by spark erosion before the abrasive grains cut the material and (ii) self sharpening of the grinding wheel brought about by the electrical discharges. The primary limitations of the process was found to be the high wear rate of the wheel, which could be circumvented by replacing the resinoid bond of the wheel by tungsten , which is quite resistant to spark erosion.

Rajurkar [13] have reported the characteristics of EDM-grinding hybrid process, which they call as Abrasive Electrodischarge Grinding (AEDG). The experimental set-up comprises a grinding attachment assembled on EDM die-sinker. Machining experiments have been conducted on Al-Sic and titanium alloy. Their viewpoint of the process has been to study how abrasion could enhance EDM performance , and for this reason , a fine grit wheel is used. The current , pulse on-time and wheel speed have been identified to be the main parameters influencing the process responses for a particular wheel and servo reference voltage setting. The enhancement of the material removal rate on introducing abrasion into the process has been studied in comparison to conventional EDM and EDM with a rotating graphite electrode (EDG), as a function of wheel speed and pulse on-time , an increase in wheel speed has been observed to provide a higher material removal rate in AEDG due to enhanced abrasion. Similarly, with an increase in the current, more of material is removed on account of intensified electroerosion.

Malkin and Cook [14] have carried out experimental investigation of fracture wear. Most of the wear consists of grain and bond fracture, particles with relatively more bond fracture occurring with soft wheels. They found that the rate at which fracture wear occurs is directly related to the grinding forces and the amount of binder in the wheel. The attritious wear, although contributing insignificantly to the total wear, is the most important form of wear as it is directly related to the size of the wear flats, grinding forces, and controls grain and bond fracture.

Koshy [15] presented the mechanism of material removal in electrical discharge diamond grinding. The role of current and wheel speed, on the material removal rate, the grinding forces and power is studied to elucidate the same. The characteristics of normal forces with varying current shows that the normal force decreases with increasing current for all wheel speeds. It is also seen that for a particular current , the normal force is higher for a larger wheel speed. The reason mentioned for above behaviour is more thermal softening at higher current. Similar experiment for tangential force shows somewhat different behaviour. At zero current the tangential forces decreases with wheel speed, the trend of which reverses with a current flowing through the gap. The characteristics also exhibit distinct maxima with respect to current for each wheel speed. The maxima shifts towards higher values of current with increasing wheel speed. Furthermore, the grinding power is observed to decrease due to same reason of thermal softening of work material.

Koshy [16] Presented the behaviour of cemented carbide while diamond grinding with electrical spark discharges incorporated at the wheel work interface. The effect of current and pulse on-time of the discharges on the material removal rate and grinding forces is studied to elucidate the mechanism of material removal. Relationship between the material removal rate and current at different pulse on-time, shows that, MRR is maximum at 0.5A for different pulse on-time. The MRR on reaching maximum decreases thereafter with further increase in current. It is also observed that within the investigated range of current, MRR increases with a decrease in pulse on-time for a particular value of current. Dominance of plastic deformation over microcracking , dislodging of abrasive grains and increase in gap-width are some of the reasons mentioned for decrease in MRR at higher current. The overview of different characteristics indicates that the discharges enhance the grinding performance by effectively declogging the wheel surface.

1.3 WHY THE NEW PROCESS IS NEEDED :

To appreciate the motivation for the development of EDDG process, it is worthwhile to review certain characteristics and the problems associated with grinding and EDM of hard materials to understand how they assist each other when combined.

Every machining , by nature, calls for a tool material harder than the workpiece. Grinding of hard materials therefore becomes a problem as the work-material hardness approaches that of diamond, which is the hardest known abrasive. In addition to this

grinding of hard material is characterised by high normal force because indentation of abrasive grains into workpiece becomes difficult [17].High normal force results in elastic deformation of grinding machine and reflects badly on the machining accuracy. In view of above circumstances it becomes more and more important to investigate and determine the means of lowering the resistance of work material to machining. Hybrid machining processes are possibly the key to this problem. ECG of Al_2O_3-Mo cermet, for instance, involves lower grinding force and specific grinding energy in comparison to conventional diamond grinding, as the electrolyte action weakens the Mo bridges that bind the hard Al_2O_3 grains [18]. In EDDG, electrical spark discharges are utilised to thermally soften the work-material on a microscopic scale to facilitate grinding and reduces grinding forces.

During the grinding process of hard material wear-flats are formed rapidly on the abrasive grains owing to intense attritious wear. This process is well known as glazing of the wheel. Another related phenomenon in grinding is wheel loading which results in the formation of grinding swarf near the chip pockets over the wheel surface. These phenomena collectively give rise to a time-dependent increase of grinding forces and power, and undesirable vibration. Glazing and loading of grinding wheels are serious hindrances to achieve good machining accuracy and surface finish. These problems thus demand for frequent dressing of the wheel, to maintain a wheel topography for effective grinding. This leads to considerable loss of both wheel material and productive machining time. The volumetric diamond wheel wear while grinding polycrystalline diamond, for example , is fifty times the volume of material removed

[19] This implies that more times is spent on dressing the wheel , rather than machining In EDDG , dressing of the grinding wheel is continuous and in-process. as the bond material is subjected to spark erosion. This obviates the need to interrupt machining for dressing the wheel.

Presently mechanical methods are widely practised where dressing is performed by abrasion of the relatively soft bonding matrix [20]. These procedures have the limitations of acute wear of the dressing medium and the possibility of the loss of abrasive grains by way of grain fracture or pull-out. But electrodischarge dressing [21] is highly result oriented and alleviates these difficulties. Here mechanical shearing of abrasives is absent as dressing is performed by bond erosion. A maximum protrusion height close to 60% of grain dimension is achievable by this method [22], whereas the one obtained through mechanical methods will be lower, depending on the efficiency of dressing. In addition , the negligibly low dressing forces in electrodischarge dressing help retain good form accuracy of the wheel and facilitate dressing of even thin wheels. Moreover, a wide range of grit sizes and concentrations can be accommodated while electrodischarge dressing by just changing the discharge parameters. Mechanical methods of dressing, on the other hand , would require a large inventory of suitable dressing wheels of different specifications for accomplishing the same task.

EDM is an inefficient machining process. Thermal modelling of the process has indicated [23] that the fraction of the molten material which is physically not removed

but redeposited on the parent material surface could be as high as 80% . The recast layer and the heat affected material immediately beneath contains numerous microcracks which degrade the fatigue strength of the material. In EDDG, the crack infested layer can be ground off by appropriately selecting the grit size of abrasives used in the wheel. The rate of material removal is also improved considerably.

EDM of composite materials containing electrically nonconducting phases possess a few problem. The nonconducting material particles hamper the process stability and impede the material removal process resulting in very low stock removal rates. More serious is the risk associated with die-sinking of this kind of materials [24]. As machining progresses , due to inhomogenity of the work material , if by chance a localized layer of insulating material surfaces up, the control system of the machine tool would misinterpret the situation as an open circuit condition. This would result in a feed motion being imparted to the electrode which can result in collision and consequent damage . These problems are taken care of in EDDG. The MRR is enhanced as the abrasive grains remove the nonconducting material particles expending little effort, with the spark discharge having thermally softened the surrounding binding material. Chances of potential collisions are also reduced considerably by the incorporation of abrasion into EDM . The rotating wheel , moreover, considerably improves the flushing at the interelectrode gap, which is most important with regard to process stability.

1.4 PRESENT WORK :

The thesis comprises theoretical as well as experimental investigation of the electro-discharge diamond grinding process. In studying the EDM-grinding hybrid machining process , present work emphasise on the role of electrical spark discharges incorporated at the wheel work interface in enhancing the grinding performance. Experiments have been conducted on high speed steel to find the effect of current , voltage, pulse-on-time and duty factor on the material removal rate and grinding forces, whereas Koshy [15] stressed on current and wheel speed.

Thermal analysis is presented in chapter 2. Description of the experimental set-up and procedure is given in chapter 3 and the associated results and discussion constitute chapter 4 of the thesis. The conclusions drawn from the present work are enumerated in chapter 5, possible avenues for future research are also outlined.

Chapter 2

THERMAL ANALYSIS

During the course of grinding the normal force component initially increases with time on account of the formation of wear-flats on the diamond grains by a combination of abrasive and chemical phenomena and later stabilizes at an equilibrium value. Results of Grahm & Nee [25] indicate that the wear of the wheel, for a given set of grinding conditions, is related to the hardness of the workpiece, and the rate of change of normal force during the course of grinding.

The normal force was found to depend mainly on the hardness of the work-material and to be independent of the cutting speed. The tangential force component, on the contrary, while being insensitive to work hardness, was observed to decrease with an increase in cutting speed [26].

In electrical discharge diamond grinding the spark discharge thermally softens the work-material in the grinding zone and thus reduces the normal force. A simple mode for assessing the reduction in normal force, due to the incidence of spark discharges on the HSS work-piece is presented below.

The normal force component in grinding originates from the physical interaction between the abrasive grains and the work. The extent of abrasive-work interference in grinding depends on the topography of the wheel and process kinematics and is stochastic in nature. However, for simplicity, it is expedient to consider a single

spherical grain of radius "R" ploughing through a plane work surface to a depth "d" (Fig. 2.1). The normal force, F_n, in this case is given by

$$F_n = H\,A_c^P \qquad \text{..............................} \quad (2.1)$$

where, H is the hardness of the work-material and $A_c^P = \Pi/2(2Rd - d^2)$ is the projected area of contact in a plane perpendicular to the line of action of F_n.

In electrical discharge diamond grinding, a spark discharge of EDM incident on the work-material just ahead of the grain would bring about a hardness gradient across the depth of cut due to a temperature gradient. The point-heat source model for the anode erosion is used, to compute the temperature gradient in the material due to a single spark [27].

In electrical discharge machining tool electrode as cathode and work-piece as anode are separated by dielectric fluid. During operation, a voltage applied across a predetermined gap causes the dielectric to breakdown. A plasma channel, surrounded by vapour bubbles, grows during given pulse on-time T_{on}. Unlike a gas, the surrounding dielectric fluid restricts the plasma growth, thus concentrating the input energy "VIT_{on}" in a very small volume. This results in energy densities of up to 3 J/mm^3, causing local plasma temperatures to reach as high as 40,000 ^0K. Viscosity effects are thought to be responsible for the plasma shape of Fig. 2.2.

During this pulse on-time, the high-energy plasma melts both electrode by thermal conduction but limited electrode vaporization occurs due to the high plasma pressure. Thermal conduction and melting are dominant mechanisms for electrode erosion, while the physics of plasma bubble is not well understood. By assuming a point heat-

source model for the anode erosion, the necessity of a complex plasma model to supply boundary conditions for electrode conduction model is avoided. Several simplifying assumptions are applied with reasonable accuracy to anode erosion.

The main assumptions of the model are the following

1. There is one spark per pulse, and the plasma radius at the anode end (a_A of Fig. 2.2) grows with time as $a = a_0 x T_{on}^{3/4}$.
2. Effective (average) thermophysical properties of the anode material apply over the temperature range from solid to liquid melt.
3. The erosion mechanism is by melting.
4. A constant fraction, F_A, of the total power "VI" is transferred to the anode. This fraction is independent of current and pulse on-time, but may change when either electrode or the dielectric fluid is replaced.
5. Heat of fusion of the anodic material is ignored, as it incurs a maximum error of just about 2%.

Fig. 2.2 is a schematic representation of the conduction model depicting the Gaussian-distributed heat source incident upon the anode surface as well as the melt-front position which is symmetric in the θ direction. The governing partial differential equation for the determination of the temperature distribution T(r,z,t) due to unsteady-state conduction into the anode material for the model is

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \qquad \text{................ (2.2)}$$

where $\alpha = k_t/\rho C_p$ is the thermal diffusivity.

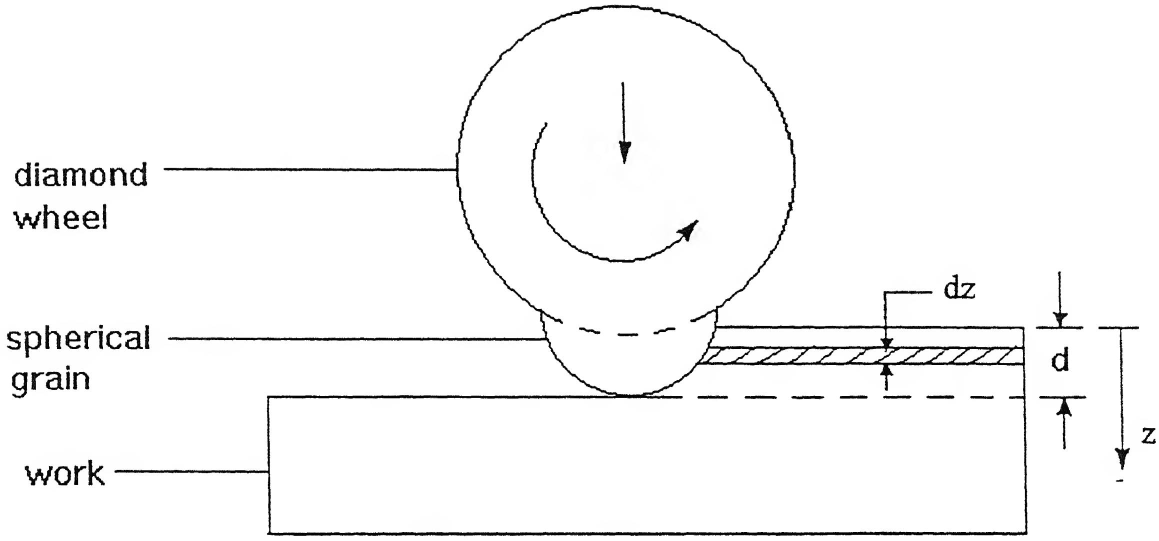


Figure 2.1 Illustration of the model for estimating the reduction in normal force due to the incidence of spark discharges

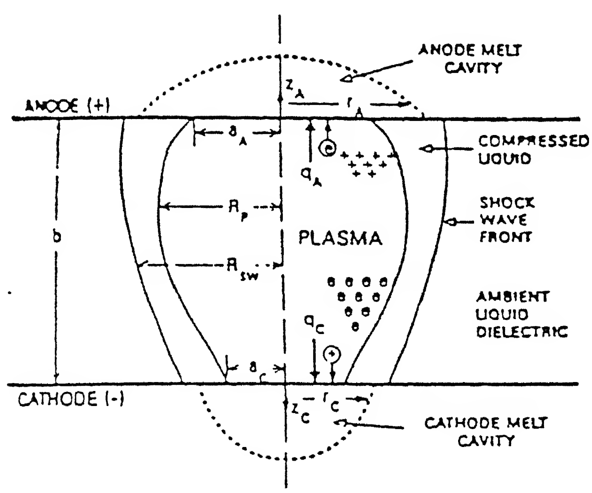


Figure 2.2 A schematic diagram of the EDM process showing the circular heat sources, plasma shape, and melt cavities in both electrode after a certain pulse on-time.

The associated initial condition (I.C.) and boundary conditions (B.C.) for the above partial differential equation are

I.C.. $t=0$ $T=T_0$

B.C. $t>0,\ z=0$ $-k_t\dfrac{\partial T}{\partial z} = q(r)$ for $0<r<q(t)$

$= 0$ for $r>q(t)$

$t>0,\ z=r=\infty$ $T=T_0$

where, T_0 is the ambient temperature of the solid and k_t is the thermal conductivity. The energy flux q(r) is given by

$$q(r) = q_0 \exp(-r^2/a^2) \qquad \text{......................................(2.3)}$$

where 'a' is the radius of the disk over which the flux is incidence.

In order to obtain an analytical solution to the heat-conduction equation (2.2) ,Gaussian flux is replaced by an equivalent uniform flux. The approach used is the one proposed by Rykalin [29] wherein the disc radius 'a' is replaced by r_g, the "focus spot". The energy distribution is then considered uniform over this new radius. Based on an equal energy partition, the relation between a and r_g is

$$r_g = a/e \qquad \text{..(2.4)}$$

Temperature distribution for a fixed circular disc source obtained from the analytical solution given by Carslaw and Jaeger [30] is used.

$$T(r, z, t, r_g) = \frac{r_g q}{2k_t}\int_0^\infty J_0(\lambda r) J_1(r_g\ \lambda) \times \frac{d\lambda}{\lambda} \qquad \text{......................................(2.5)}$$

where , J_0 and J_1 are bessel functions of zero and first order, respectively, and

$$x = e^{-\lambda z}\,\psi\left(\frac{z}{2\sqrt{t\alpha}} - \lambda\sqrt{t\alpha}\right) - e^{\lambda z}\,\psi\left(\frac{z}{2\sqrt{t\alpha}} + \lambda\sqrt{t\alpha}\right) \quad .\ldots\ldots\ldots..(2.6)$$

furthermore , for the known power input $F_A VI$, the incidence of the energy flux upon the anode is

$$q_A = \frac{F_4 VI}{\Pi r_g^2(t)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.7)$$

The axial temperature at any time is provided by a much simpler expression which is derived as a special solution of equation (2.5) [15]

$$T(z) = \frac{2q\sqrt{t\alpha}}{k_t}\left[\phi\left(\frac{z}{2\sqrt{t\alpha}}\right) - \phi\left(\frac{\sqrt{z^2 + r_g^2}}{2\sqrt{t\alpha}}\right)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.8)$$

where, ϕ represents the integral complementary error function . The material constants used for computation are k_t=25 W/mk and α =6.83 m^2/s for high speed steel work material . The fraction pulse power incident on the work is assumed to be 8% [29].

The hardness H(z) at a depth , z , would depend on the temperature, T(z) . The normal force ,F_n^P , corresponding to this situation can be calculated as

$$F_n^p = \frac{2}{d}\int_0^d H(z)\,A_c^p(z)\,dz \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.9)$$

High speed steel retains about 80% of its hardness upto a temperature of 600 ^{0}C. At higher temperature the hardness decreases rapidly at first and gradually thereafter as the temperature approaches the melting point [28]. The hardness becomes zero at the melting temperature

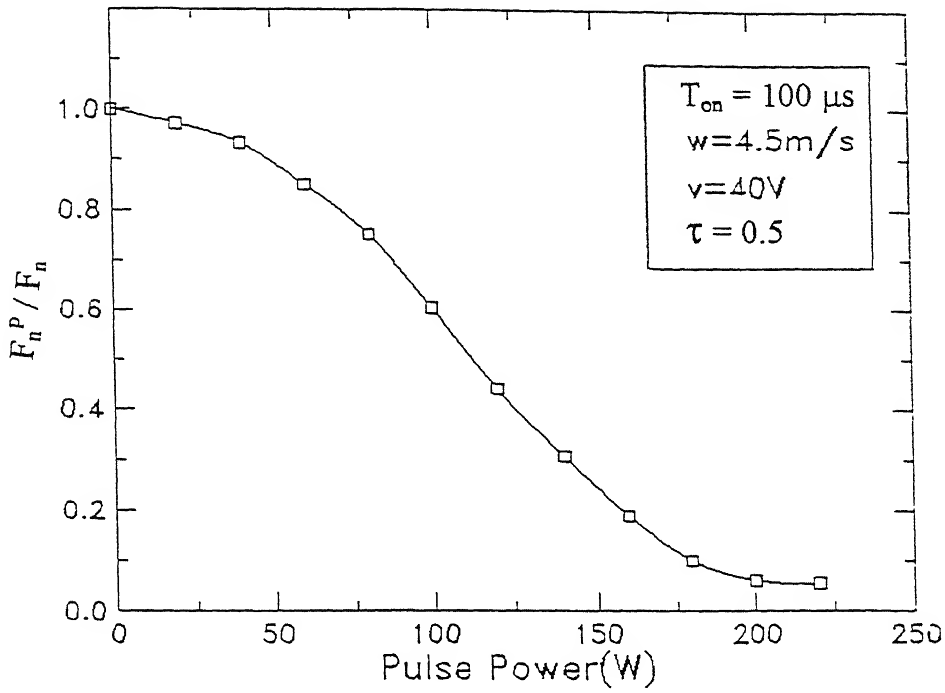


Figure 2.3 The effect of pulse power on F_n^P / F_n for high speed steel workpiece material .

(1250^0 C). In the present work for computation , H(z) is evaluated as a function of the temperature, T(z), by fitting piecewise polynomials.

The model is simulated to study the effect of pulse power on F_n^P/F_n, for comparing the normal force due to electrical discharge diamond grinding (F_n^P) with normal force due to grinding only (F_n) Results show that F_n^P/F_n decreases with increase in pulse power. The reasons for above phenomenon, as already stated, is that the temperature, T(z), due to spark discharges of workpiece surface decreases from surface to bottom as per mentioned equation 2.8. This increase in temperature gradient also increases the hardness gradient which would ultimately result in lower normal force.

Chapter 3

EXPERIMENTAL SET-UP AND PROCEDURE

This chapter describes the experimental set-up and the details of experimentation.

3.1 EXPERIMENTAL SET-UP :

Experiments were carried out on a ELECTRA die-sinking type spark erosion machine equipped with a solid-state power supply, schematic diagram of which is shown in Fig. 3 1. The grinding wheel, which is negatively charged, is mounted on the ram of the machine to rotate. The metal-bonded diamond wheel is mounted so that its axis is parallel to the machine table. The work-piece, charged positively, is mounted on a dynamometer which in turn is mounted on the base of the machine. The grinding wheel is driven with the help of a variable-speed controlled motor. Here, the servosystem of EDM machine is used to maintain predetermined spark gap, width of which depends on the gap voltage. To control the electrical parameters like gap voltage, current, pulse on-time, and duty factor the EDM Power supply unit, drawing power from AC source through voltage stabilizer, is used. Servo sensitivity of servosystem is also controlled from EDM Power supply unit.

3.2 TRUING TECHNIQUE:

Wheel truing is defined as the act of restoring the cutting ability of a grinding wheel by removing the worn out abrasive materials from the cutting face and sides of the

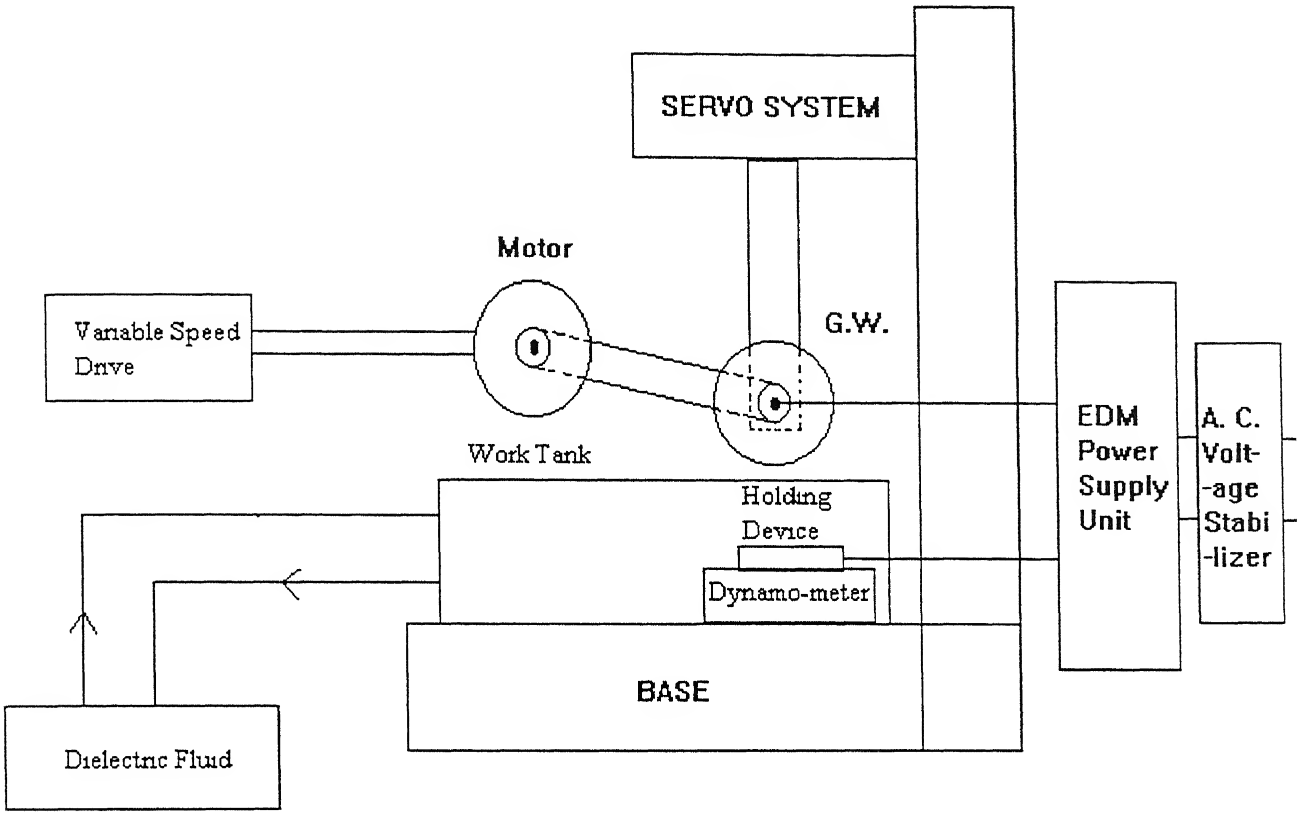


Figure 3.1 : Schematic diagram of the full set-up of EDDG.

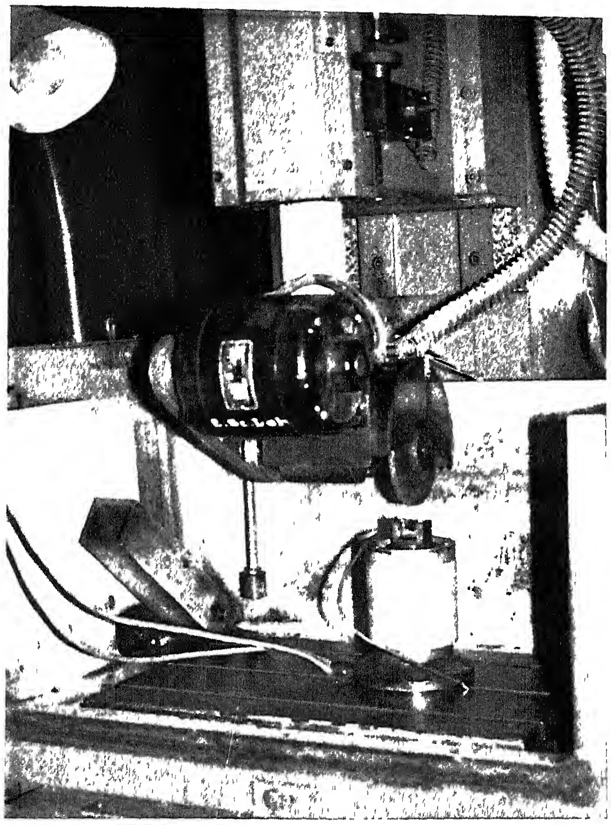


Figure 3.2 : **Photograph depicting the grinding attachment mounted on the ram of the EDM machine**

wheel so that it would run true with respect to the axis of rotation and produce perfect round or flat work. After the diamond wheel is mounted on the spindle, first of all it goes through truing process which is done with the help of a silicon carbide wheel (C60L5V), which run in mesh with the diamond wheel. Truing process is accomplished by abrasion of the bond by debris generated at the interface of the two wheels During the process precaution is taken so that no slip exists between grinding and truing wheel, which is achieved by orienting their axes such that their peripheral velocities are not collinear along the line of contact. The process is carried out till the wheel run-out is less than 10 μm.

3.3 DRESSING TECHNIQUE:

Wheel dressing is defined as the act of improving the cutting action. It becomes necessary from time to time during the course of working to correct uneven wear and to open up the fresh sharp grains on the surface of the wheel so as to obtain efficient cutting operations. Just after the truing process in order to obtain standard wheel topography, wheel is dressed by electrodischarge dressing under identical discharge conditions (see table 3 1) before each experiment. Sufficient grit protrusion height, P_h, is obtained under high discharge energy conditions but at the expense of dislodging some abrasive grains. The dressing conditions employed in the present study were selected to avoid contact between the abrasive grains and the dressing electrode and to

remove radially about 50 μm of the wheel material (approximately 30% of the grain dimension) in reasonable time.

The choice of electrode material is important for electrodischarge dressing of diamond wheels, because at high temperature diamond is transformed to graphite, in presence of certain metallic elements. The colour of the wheel surface was observed to turn black during electrodischarge dressed with steel electrode, indicating graphitization of protruding abrasive grains. At 900 C in presence of iron remarkable graphitization of diamond has been observed [31]. As literature indicates, out of several materials studied by various researchers, copper and gold introduce no thermal erosion in diamond. Since copper is cheaper than gold, dressing of wheel was hence carried out with copper electrode employing positive polarity.

3.4 MEASUREMENT OF FORCES:

The forces were measured by extended octagonal-ring type strain gauge dynamometer shown in Fig. 3.3. In bonded-wire strain gauge , the electrical resistance is changed when it is deformed in the longitudinal direction. Strain gauges on the ring were connected to form two separate Wheatstone bridge circuits for measuring the vertical and horizontal forces independently as shown in Fig. 3.4. Voltage is applied across A and B and output voltage obtained across C and D is amplified and recorded. The gauges 1,2,3,4 at 90^0 to the vertical axis measure the force component F_t, and the gauges 5,6,7,8 at 50^0 to the vertical axis measure the force component F_n, the dynamometer was calibrated in both horizontal and vertical directions using known

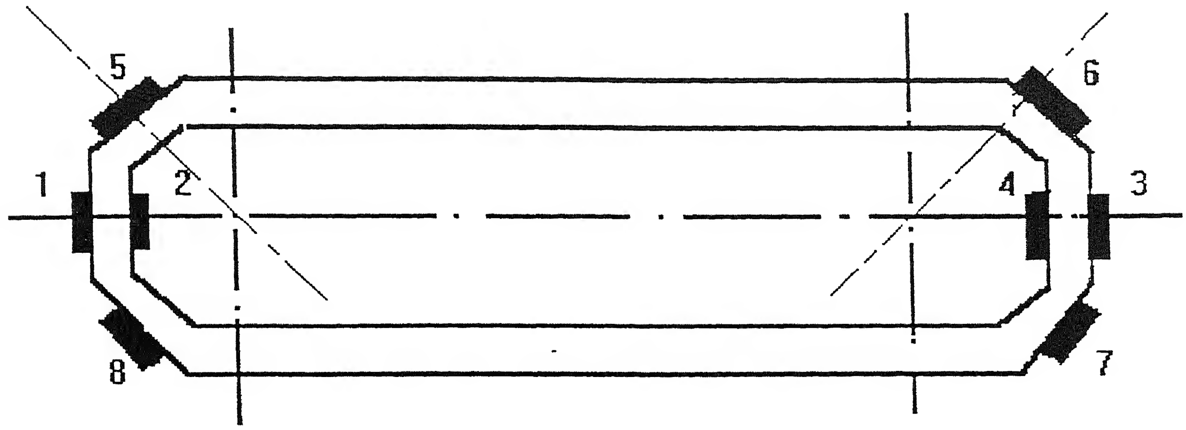


Figure 3.3 Extended octagonal ring of dynamometer

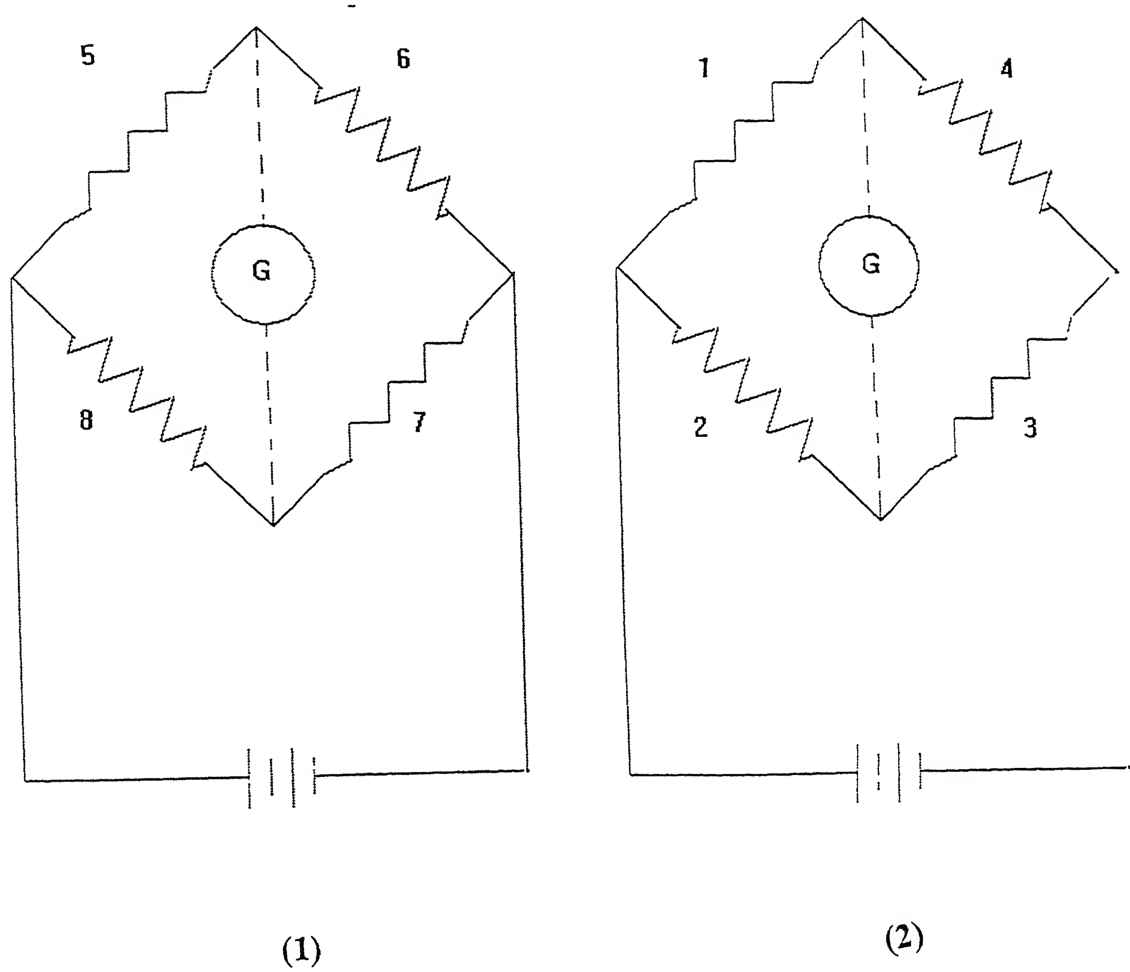


Figure 3.4 Wiring Diagram (1) Horizontal force circuit (2) Vertical force circuit.

dead weights and the forces were recorded on a two channel pen recorder. The cross sensitivity between the components was also checked. This gives the following equations for F_n and F_t in terms of pen deflection R_x and R_y on the recorder,

$$F_n = 78.103R_x - 2.789\ R_y$$

$$F_t = 37.192R_y - 4.184\ R_x$$

3.5 MEASUREMENT OF MATERIAL REMOVAL RATE:

The material removal rate was calculated by measuring the weight loss of the workpiece on machining for a period of five minutes.

3.6 EXPERIMENTAL PROCEDURE:

Before the experiments, the machine along with the dynamometer and electrical equipment were allowed to warm-up for 15 minutes so that they all reached a stable condition. After reaching a stable condition, all the parameters like voltage, current, pulse on-time, duty factor, servo sensitivity and wheel speed were set and the machining was started. During machining the rotating wheel is fed downward by the servo control of the EDM-machine for material removal in cut-off configuration (Fig. 3.5) The downfeed of the rotating wheel is regulated automatically by the EDM servo system such that the metallic wheel bond and the work surface are physically separated by a definite gap, the width of which depends on the local breakdown strength of the dielectric for a particular servo reference voltage setting. The

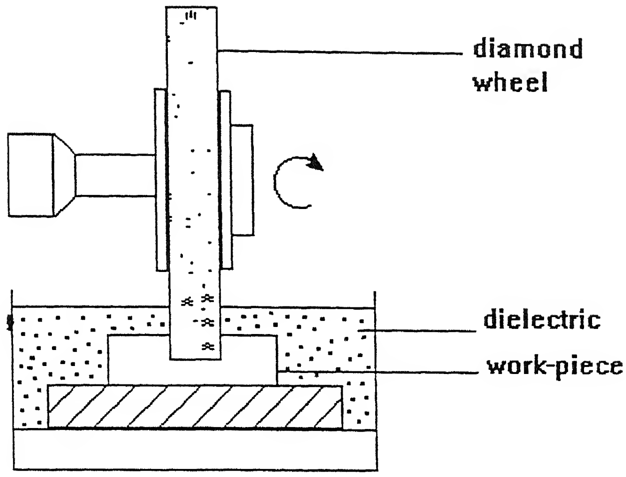


Figure 3.5 Kinematics configuration of the experiment set-up.

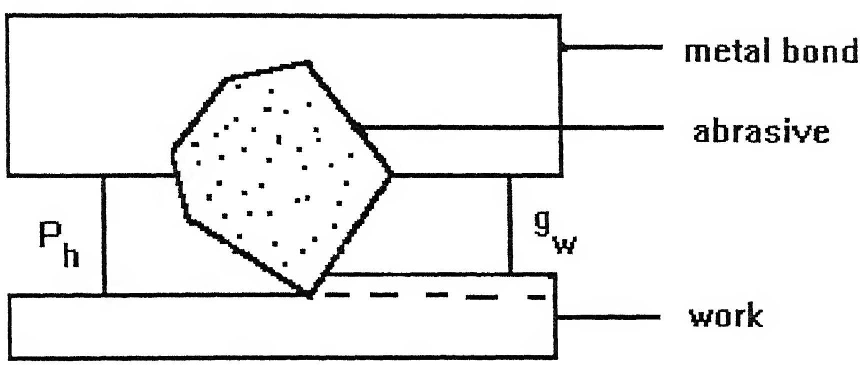


Figure 3.6 Schematic representation of a section of the wheel-work interface in EDDG.

is thus simultaneously subjected to heating due to electric sparks occurring between the wheel bond and the work, and abrasion by diamond grains with protrusion height, P_h, more than the inter-electrode gap-width g_w (Fig. 3.6). In conventional grinding operations, a part of the input energy is expended in sliding contact between the wheel bond and the workpiece [32]. In the configuration above, since the non-conducting diamond grains alone are in contact with the work, such loss in friction energy is non-existent.

After machining the MRR was calculated by measuring weight loss of the sample and forces were calculated by putting the values of pen deflections R_x and R_y in the equations of F_n and F_t. Preliminary experiments indicated higher MRR with work as positive polarity and hence this was adopted throughout the experiments. Since the performance characteristics of diamond wheels of even the same specification are prone to vary, the same wheel was adopted for all the experiments. The specifications of the diamond wheel and the dressing parameters employed are listed in Table 3.1.

Wheel	
1A1 diamond wheel, 5.7mm thick, 100mm diameter	
G80/100 C75 , Bronze bond.	
Dressing	
Voltage	60 V
Current	10 A
Pulse on-time	100 us
Duty factor	0.5
Wheel Speed	60 m/min.
Duration	2 min

Table 3.1 Wheel specification and electrodischarge dressing parameter

In order to evaluate the grinding performance obtained in EDDG, experiments have also been conducted by switching off the current, to correspond to conventional diamond grinding. It has been observed that a negligibly small current of approximately 0 04 A flows through the gap at this setting for the purpose of gap sensing.

3.7 MACHINING CONDITIONS:

The effect of the following variable on the material removal rate and grinding forces was investigated to perceive the underlying physics of the process.

Work piece

High Speed Steel, Dimension 1" x 1/4" x 1/4"

Pulse on-time

20 μs, 50 μs, 100 μs

Voltage

25 V, 40 V, 60 V

Duty Factor

0.4, 0.52, 0.64

Wheel Speed

constant at 4.5 m/s during all experiments.

Current

varying from 0 to 6.5 A

Servo Sensitivity

Kept constant for all experiments.

Chapter 4

RESULTS AND DISCUSSION

4.1 MATERIAL REMOVAL RATE:

The progressive loss of the cutting ability of a diamond wheel while grinding hard materials is generally due to one or a combination of the following phenomena: (1) Attritious wear of grits resulting in the formation of wear flats (2) Wheel loading and (3) Pull-out of abrasives. Wheel loading refers to the adhesion of grinding debris on the active grains and the wheel bond. This leads to increased friction in grinding operations. A study on the loading of grinding wheels [34] indicates that the rate of loading is high at the outset and tends to saturate as grinding proceeds. Pull-out of grains is not quite common in fine grinding but is so during electrical discharge diamond grinding.

In electrical discharge diamond grinding only those grains with protrusion height more than the interelectrode gap-width physically interact with the work. Thus in practice, only a fraction of the number of abrasive grains interacting with the work will indeed be removing material.

Fig. 4.1 exhibits the role of current on material removal rate at different voltages during electrical discharge diamond grinding of high speed steel. The material removal rate increases with increasing current for all voltage from 20 to 60V . It is also seen that for a given value of current the material removal rate is higher for lower value of voltage.

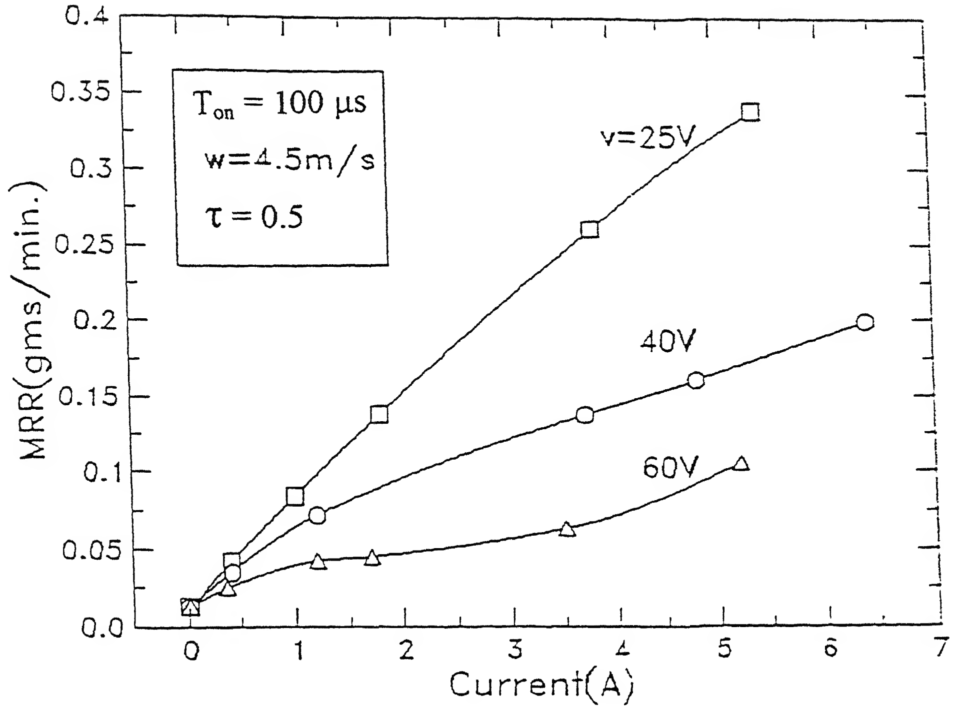


Figure 4.1 : The effect of current on the mrr at different voltage during EDDG of HSS.

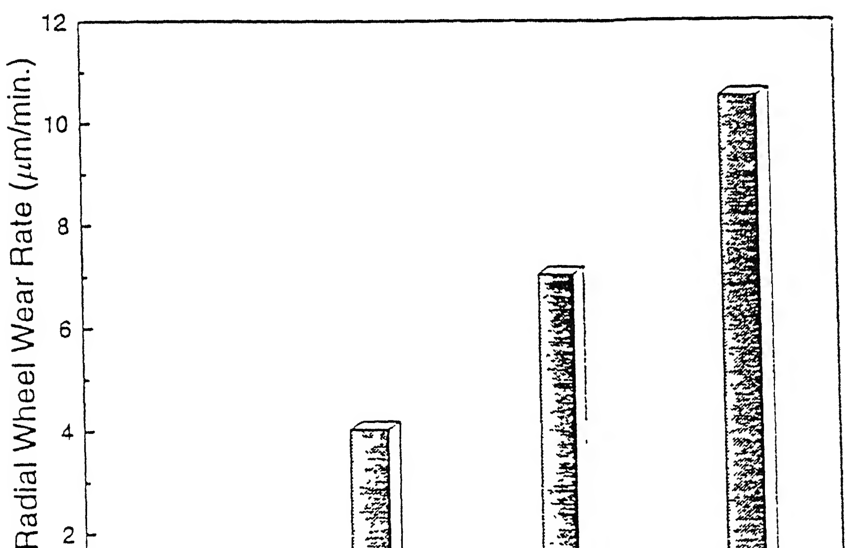
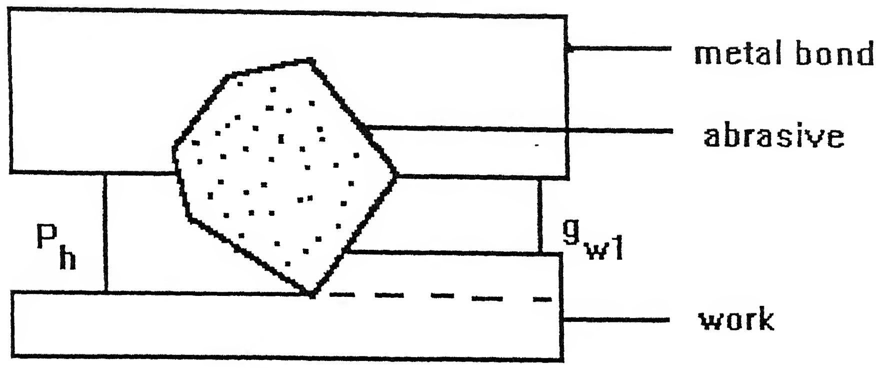


Figure 4.2 : The effect of current on the average radial wheel wear rate while EDDG of HSS. [15]

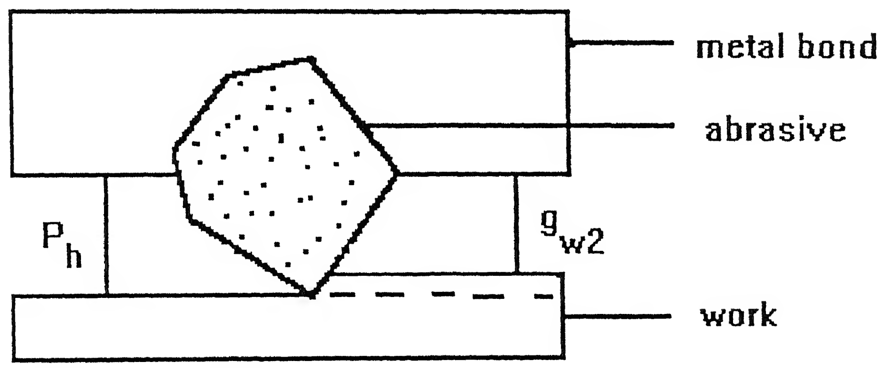
The data point corresponding to approximately 0A current pertains to grinding with no electrical discharge effect. Experiments repeated at this condition indicated that the scatter of the result was less than 5% of the mean value. The material removal capability of the wheel at 0A current is lower due to blunting of the abrasives, because while grinding of steel, diamond abrasive grains have been known to wear rapidly owing to graphitization of diamond with iron acting as a catalyst [35-37].The implications of wear-flat formation on an abrasive grain with regard to its ability to remove material are twofold: the grain-tip radius and hence the critical depth of penetration is increased while the uncut chip-thickness is decreased. Hence with the formation of wear-flats, a number of grains which hitherto have been actively involved in material removal, tend to just plough and displace but not remove material. This reduces the MRR.

To understand the mechanism of improved grinding with the flow of current in the grinding zone, it is essential to examine the magnitude and mode of wheel wear in EDDG. The average radial wheel wear rate as a function of current is shown in Fig. 4.2 [15].The wheel wear rate is seen to increase with increasing current. This implies that the continuous renewal of the wheel surface due to in-process dressing counter acts grain blunting and this enhances the grinding performance by increasing the material removal rate.

Fig. 4.1 also shows that MRR decreases with increasing voltage. The reason for this is that with increase in voltage discharge will take place at higher gap-width (g_{w2}) as compared to the gap-width at lower voltage (g_{w1}).Due to increase in gap-width the



(a)



(b)

Figure 4.3 : Schematic representation of the wheel-work interface in EDDG (a) for lower voltage (b) for higher voltage.

depth of penetration (P_h-g_{wl}) of abrasive grains will decrease (Fig. 4.3).Since the material removal rate in grinding is directly proportional to depth of penetration ,it shows significant decrease in MRR with increase in voltage. With increase in current above phenomenon becomes more and more prominent.

Fig. 4 4 shows the effect of current flowing through the wheel-work interface on material removal rate at different pulse on-time, T_{on}. The flow of current through the grinding zone by way of spark discharges is seen to beneficially increase the MRR at all pulse on-time from 20 to 100. It is also seen that in the range of current from 0 to 6A. MRR increases with a increase in pulse on-time for a particular current. This is due to enough time available for heat dissipation to the interior of work electrode which would soften the work-piece more [38].This softening effect of work-piece for higher pulse on-time reduces attritious wear of grits resulting in the higher protrusion height as compared to protrusion height for lower pulse on-time which would result in higher depth of penetration. Since the material removal rate is directly proportional to depth of penetration, it shows significant increase with increase in pulse on-time.

The effect of duty factor of the discharges on the MRR as a function of current is shown in Fig. 4 5 which indicates that the MRR increases with a decrease in duty factor in the range of current from 0 to 6 A.

Material removal parameter (A_ω) is defined as the material removed in unit time per unit normal force. The variation of A_ω with current at different duty factors from 0.4

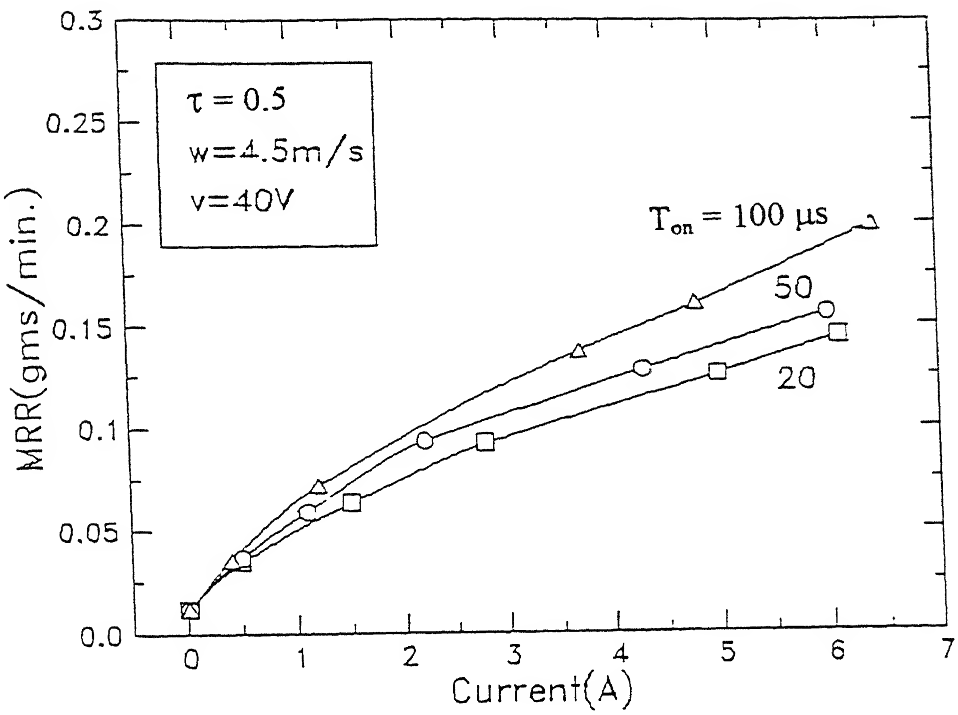


Figure 4.4 : The effect of current on the mrr at different pulse on-time during EDDG of HSS.

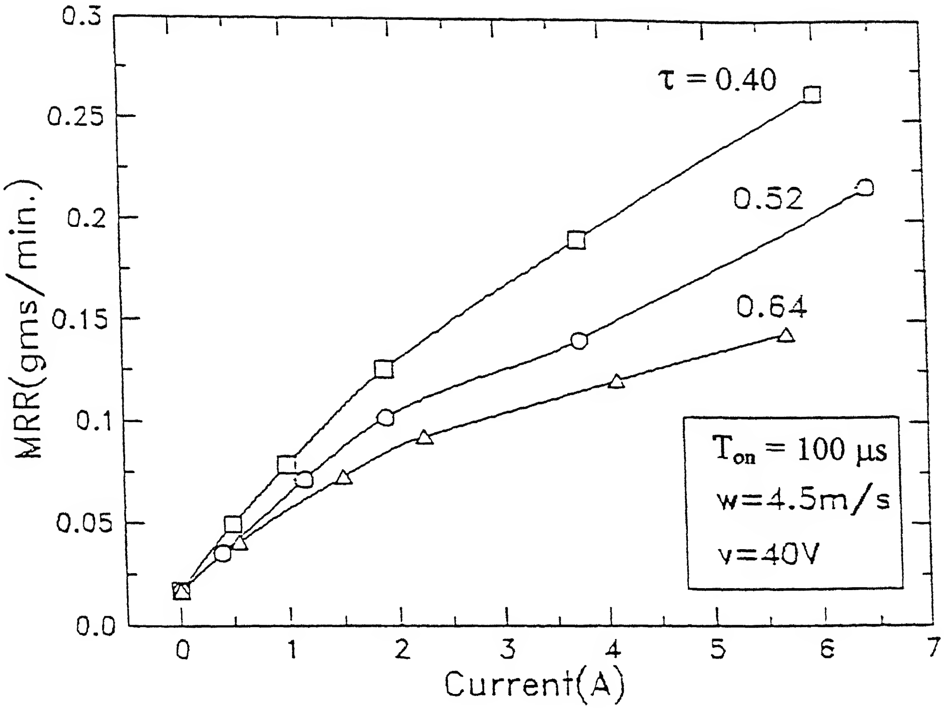


Figure 4.5 : The effect of current in the mrr at different duty factor during EDDG of HSS.

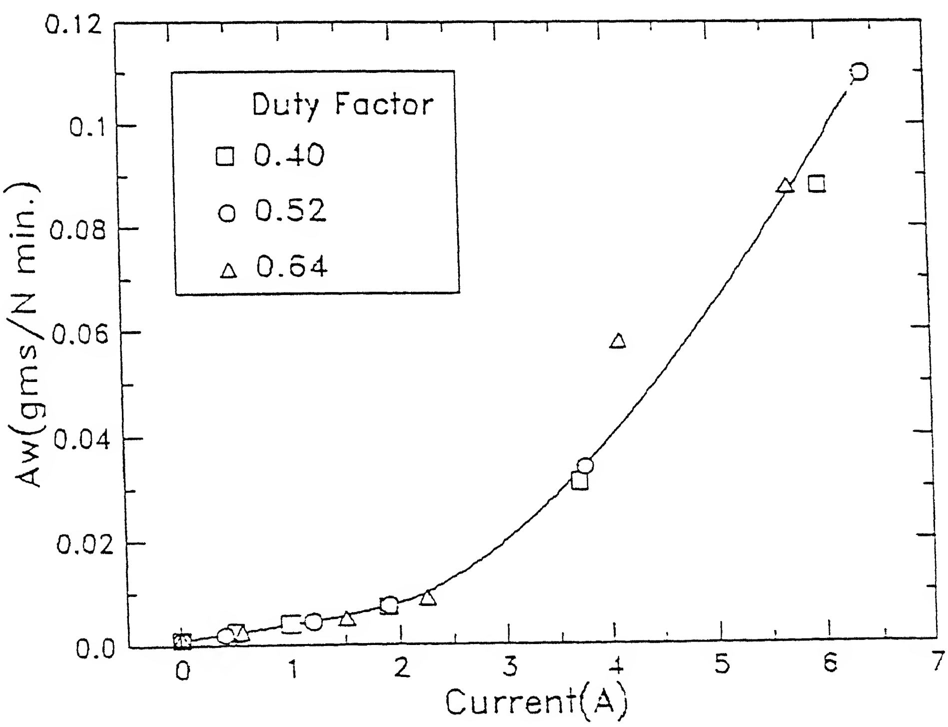


Figure 4.6 : The effect of current in the Aw at different duty factor during EDDG of HSS.

to 0.64 is illustrated in Fig. 4.6. A_ω being more or less independent of duty factor discloses the fact that the dependence of MRR and normal force on duty factor is due to the fact that a change in duty factor influences the wheel rather than the work. In electrical discharge machining, the relative volume of material eroded from electrodes depends on the respective contributions of electrons and positive ions, resulting from the ionization of the dielectric at the gap, to the total current flow [15]. Since the positive ions are about 10^4 times as massive as the electrons, the later reach the anode surface and liberate kinetic energy in the form of heat, well before the ions reach the cathode. The technological significance of this phenomenon is that undesirable wear of the tool can be minimized, if not done away with, by employing lower duty factor. This is the reason behind the reduction in the wear of the wheel on shifting towards lower duty factor observed during EDDG [12]. On extending the concept to the present experimental work, it is evident that for a particular current the extent of grain pull-out would reduce with decreasing duty factor. This results in increasing wheel-work interference which leads to higher MRR.

4.2 NORMAL FORCE:

The normal force component in grinding, although not of concern with regard to the power consumed, is important for machining accuracy considerations.

Fig. 4.7 depicts the trend of the evolution of the normal grinding force, Fn, for various values of current, normalised with respect to the initial values. It can be seen that the

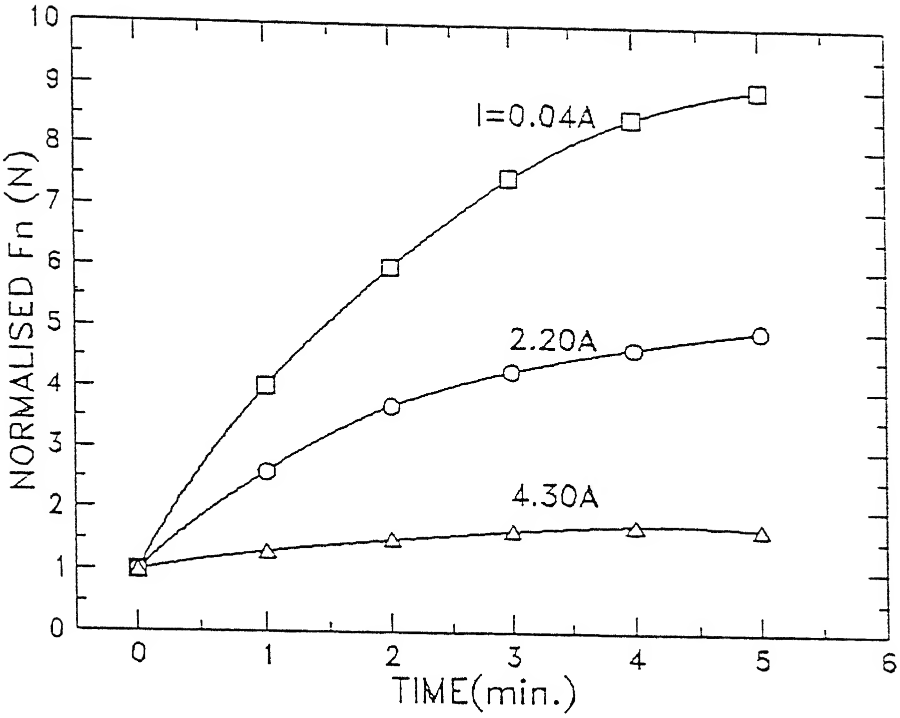


Figure 4.7 : The effect of current on evolution of the normal force during EDDG of HSS.

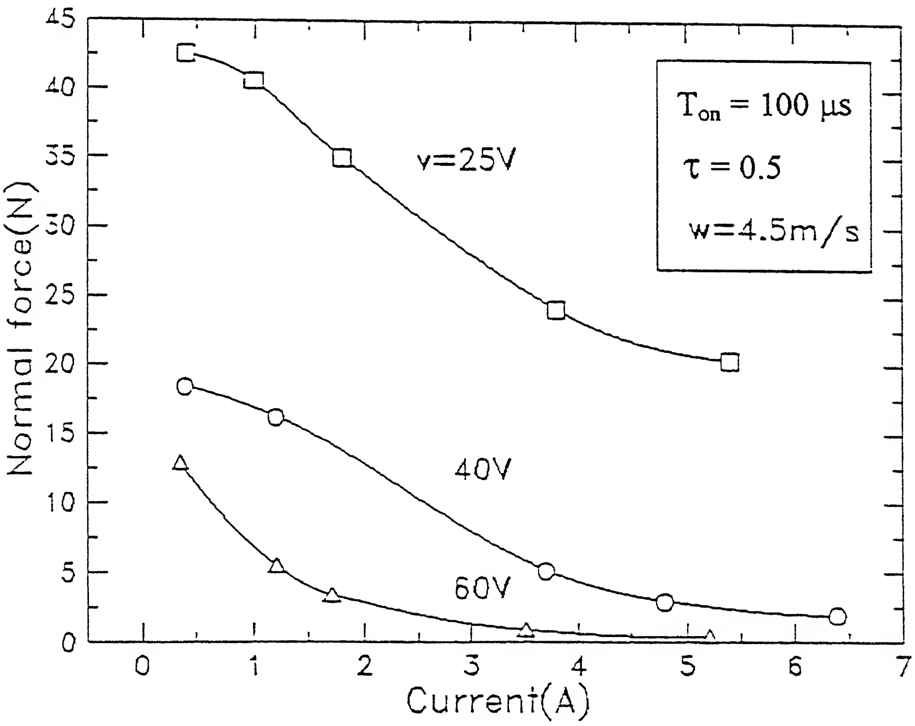


Figure 4.8 : The effect of current on the normal force at different voltage during EDDG of HSS.

normal force increases with time before attaining a steady state value. However at higher currents (4.3A) the increase in force is only marginal since the spark discharges preclude the formation of wear-flats on the abrasives.

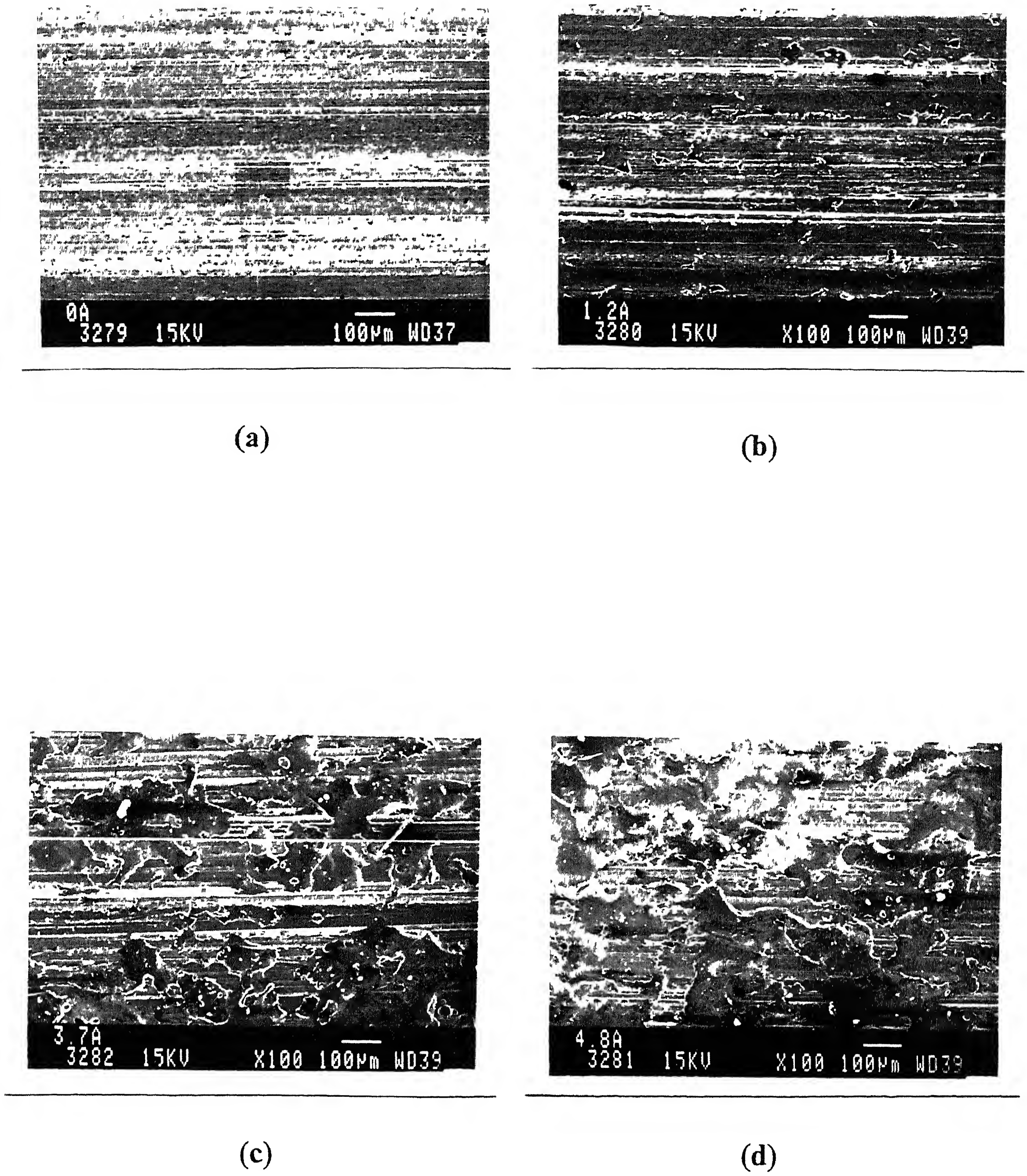
Fig. 4.8 illustrates the variation of the normal force with current at various voltages from 25 to 60 V. The normal force decreases with increasing current for all voltages. It is also seen that for a particular current, the normal force is higher for a lower voltage.

Scanning electron micrographs of ground surfaces obtained at different current clarify their effect on the normal force. Micrographs in Fig. 4 9 reveal the role of current. At zero current condition, grooves formed by the abrasive grains are visible (figure 4.9a). The black spots found are presumably graphite particles detached from the diamond grains and deposited on the machined surface. Incipient melting of the surface is evident at a current of 1.2A. The extent of melting is seen to increase with current as indicated by the micrograph corresponding to 3.7A and 4.8A current (Fig. 4.9c and d). Higher current causes more thermal softening which would result in decreasing normal force further (Fig. 4.8).

Fig. 4.8 also illustrates that the normal force reduces with increase in voltage for a particular current. The normal force and depth of cut are related as [39]

$$\mathbf{Fn \propto a^n} \qquad \mathbf{0<n<1} \qquad \ldots\ldots\ldots\ldots\ldots\ (4.1)$$

where, Fn is the normal force, 'a' is the depth of cut, and 'n' is the positive exponent.



(a) (b) (c) (d)

Figure 4.9 : Micrographs of HSS work -surfaces ground at a current of (a) 0.0A (b) 1.2A (c) 3.7A (d) 4.8A.

It can be noted from the above equation that normal force increases exponentially with depth of cut. This is, as already explained, that depth of cut varies inversely with voltage, at a particular value of current (Fig. 4.3),resulting in higher normal force at lower voltage.

Fig. 4 10 illustrates the variation of normal force with current at various duty factors. The normal force decreases with increasing current for all duty factors from 0.4 to 0.64. It is also seen that at a particular current the normal force is higher for lower duty factor.

The reason for above phenomenon, as already has been discussed, is that, at a particular current the extent of grains pull-out reduces with decrease in duty factor. This results in increasing wheel-work interference leading to higher normal force at lower duty factors.

Fig 4.11 exhibits the role of current on normal force at different pulse on-time while grinding high speed steel. The normal force decreases with increase in current for all values of pulse on-time from 20 to 100. It has also been observed that during the initial range of current, the normal force is higher for lower pulse on-time. At higher end of current, the normal force appears to become independent of pulse on-time.

The normal force depends on the hardness of workpiece. More the hardness of workpiece more will be the normal force. Higher pulse on-time would soften the workpiece more because enough time is available for heat dissipation to the interior of work electrode. This results in lower normal force at higher pulse on-time.

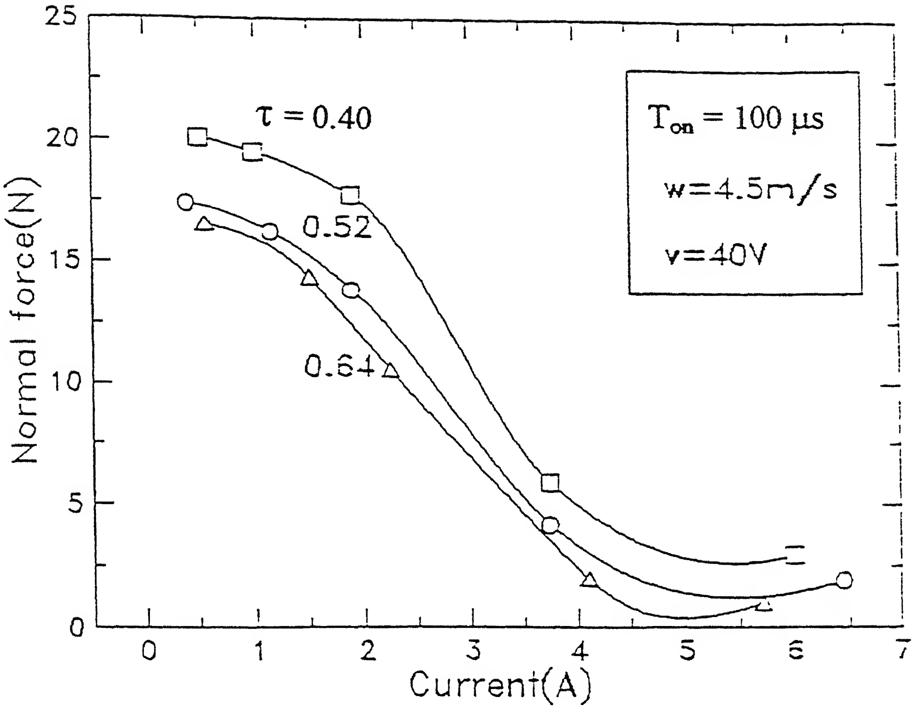


Figure 4.10 : The effect of current on the normal force at different duty factor during EDDG of HSS.

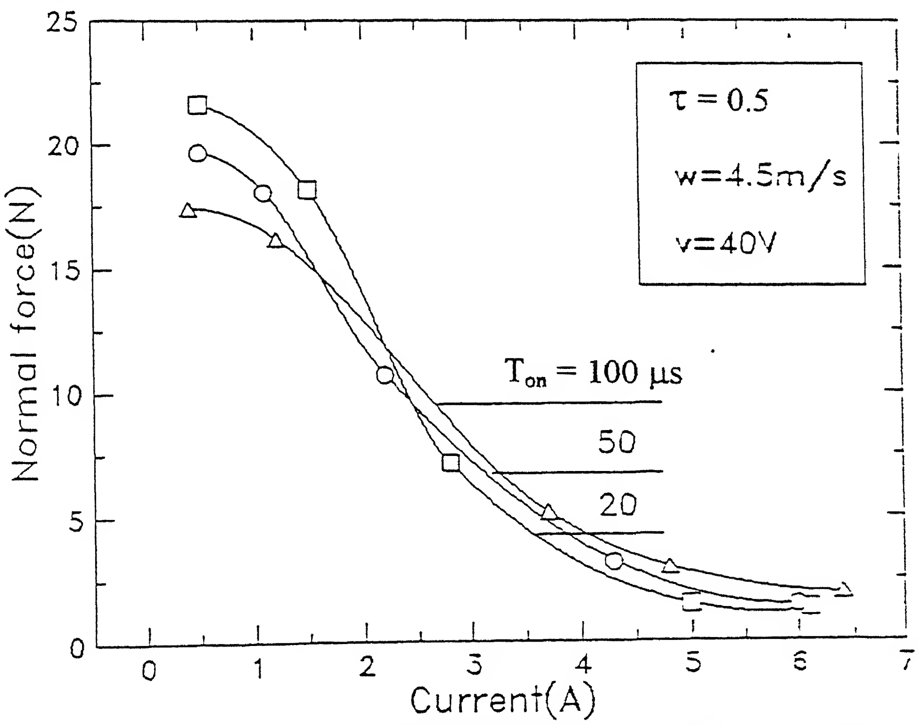


Figure 4.11 : The effect of current on the normal force at different pulse on-time during EDDG of HSS.

4.3 TANGENTIAL FORCE:

The effect of voltage on the tangential force at different current while electrical discharge diamond grinding of high speed steel is presented in Fig. 4.12. The tangential force increases initially with current and after getting a maximum value. it starts decreasing with increase in current. It is also observed that the tangential force decreases with increase in voltage for a particular value of current.

The resistance to the lateral motion of an abrasive grain comprises: (1) the force required to shear the junctions formed between the work and the grain, and (2) the force needed to displace the material ahead of the grain. These force components are influenced by the bulk physical properties of the work material.

The formation of adhesion junctions between the work and the grain at points of contact is deemed to arise out of the cold-welding process [40] The force required to shear the junction thus formed, as the grain moves, is dependent on the shear strength and the area of the junction The temperature of contact interface plays a significant role in facilitating the flow and welding of the adhesion junctions between the abrasives and the work. This explains the dependence of the tangential force on current in electrical discharge diamond grinding.

Strong adhesion force is found to initiate at a temperature about half the melting temperature of the softer metal. Above this temperature the adhesion force increases

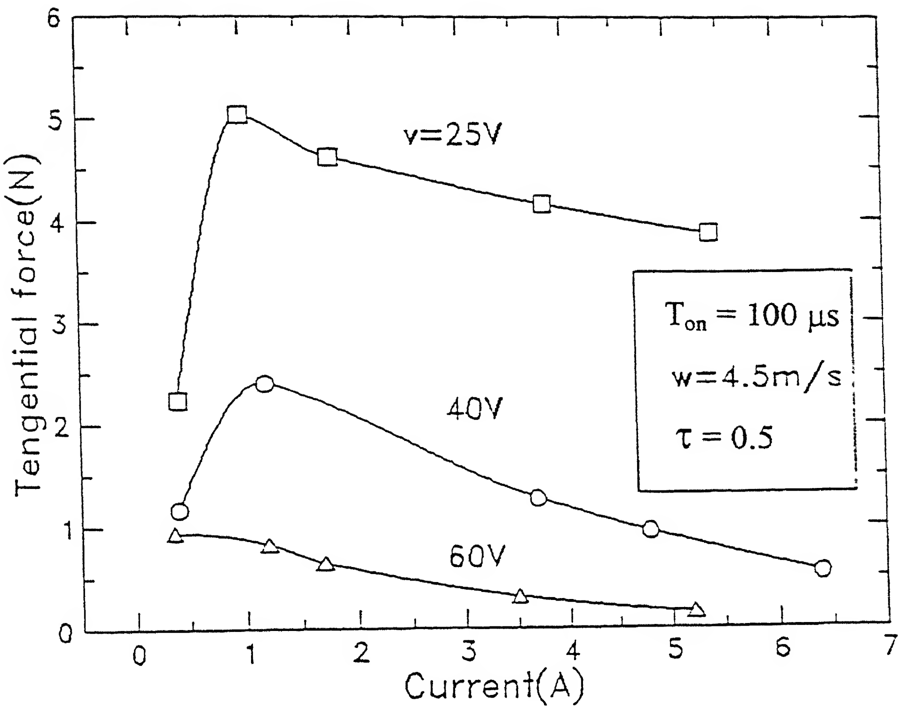


Figure 4.12 : The effect of current on the tangential force at different voltage during EDDG of HSS.

markedly to reach a maximum and decreases thereafter. The increase in adhesion force with temperature is attributed to junction growth, the rate of which is largely temperature dependent. At the temperature corresponding to the maximum adhesion force, the real area of contact is attained, a further increase in temperature results in decreasing shearing force due to work material softening which would result in lower grinding force.

It is also observed from Fig. 4.12 that tangential force decreases with increase in voltage at a particular value of current . The reason for above phenomenon is quite obvious i.e. higher the voltage higher will be the gap-width at which discharge takes place. Increased gap-width ultimately results in lower depth of cut (Fig. 4.3),which further decreases the tangential force. The above conclusion agrees well with results obtained by Inasaki [41].

The effect of duty factor of the discharge on the tangential force as a function of current is shown in Fig. 4.13. Analysis of nature of graph indicates that the tangential force decreases with the increase in duty factors in the range of current from 0A to 6A

With the flow of current through the interelectrode gap the tangential force increases with decrease in duty factor at a particular value of current. This is due to the effect of increasing wheel-work interference, with decreasing duty factor. These curves also exhibit a distinct maxima with respect to current for each duty factor. The maximum shifts toward higher values of current with decreasing duty factor because higher current is required to compensate for the decrease in the pulse energy expended on the

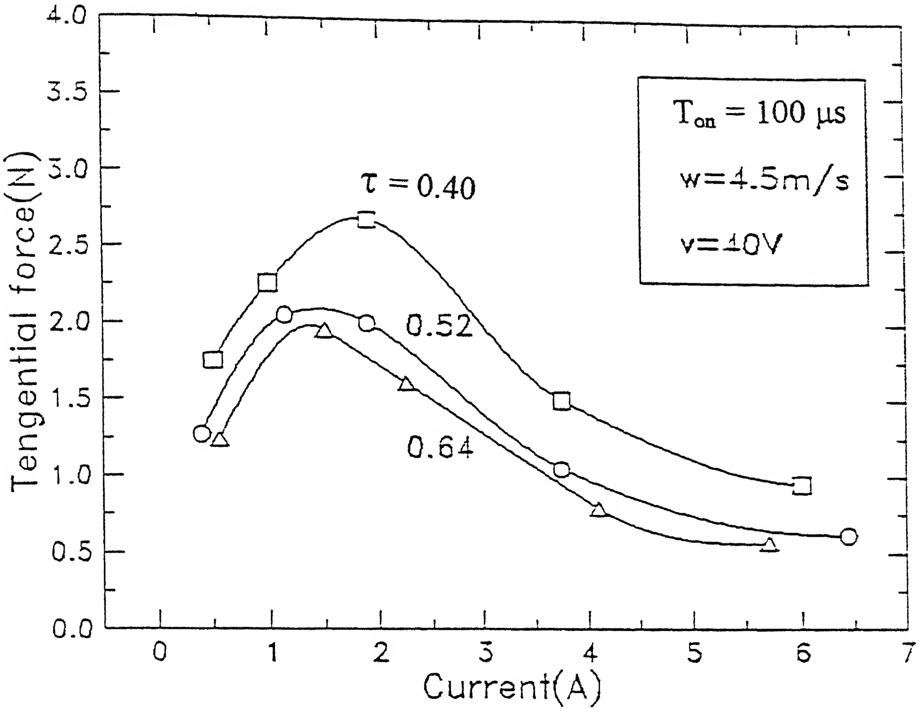


Figure 4.13 : The effect of current on the tangential force at different duty factor during EDDG of HSS.

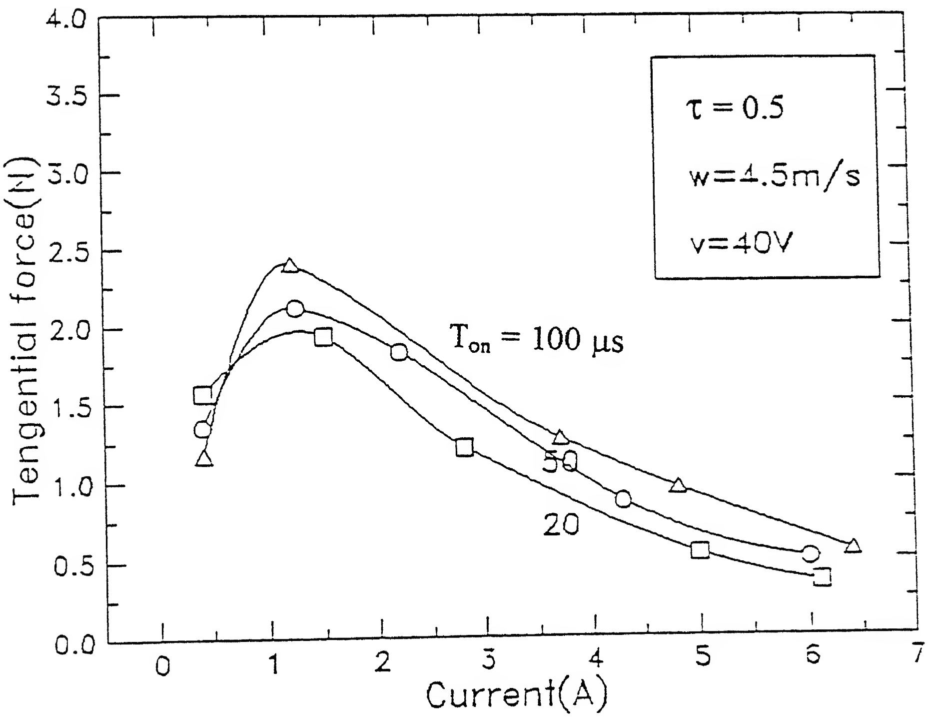


Figure 4.14 : The effect of current on the tangential force at different pulse on-time during EDDG of HSS.

work with decrease in duty factor.

Fig. 4.14 exhibits the role of current on the tangential force at different pulse on-time while electrical discharge diamond grinding of high speed steel. During initial small range of current, tangential force decreases with increase in pulse on-time ,the trend of which reverses with a more current flowing through the gap. These curves also exhibit a distinct maxima with respect to current for each pulse on-time. The maximum shifts towards lower values of current with increasing pulse on-time because lower current is required to compensate for the increase in the pulse energy expended on the work electrode with an increase in pulse on-time.

Chapter 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 CONCLUSIONS:

In this work a hybrid machining combining electrical discharge machining and grinding is proposed and the process capabilities of this new machining process are experimentally investigated. The results obtained through this study are summarized as follows:

- The combination of electrical discharge machining and grinding process can be used for improving the machining efficiency of hard and brittle materials substantially.
- It is confirmed through the experiments that this new machining process is effective to attain the high material removal rate. Electrical discharge diamond grinding experiments on high speed steel indicate that the material removal rate increases with increasing current and pulse on-time, while the same decreases with increasing voltage and duty factor.
- The hybrid machining proposed in this work is effective in decreasing the grinding force. Machining of high speed steel by this new machining process indicates that the grinding force decreases with increase in current, duty factor and voltage, the trend of which reverses with increase in pulse on-time. Electrical discharge thermally softens the work material and continuous in-process dressing of the

grinding wheel keeps the active sharp grains exposed on the wheel surface. This explains the decrease in grinding force.

5.2 SCOPE FOR FUTURE WORK:

Some of the issues which could be further investigated in future are summarized as follows:

- The mechanism of material removal in electrical discharge diamond grinding can be comprehensively studied by single-grit experiments with diamond indentors of known geometry.
- Metal bonded aluminium oxide wheels can be tried in electrical discharge diamond grinding in light of the thermal softening of the work to test their efficiency in grinding hard materials like cemented carbides which could be ground effectively only with diamond abrasives.
- A parametric study of the electrical discharge diamond grinding process to study the effect of wheel parameters like abrasive grit size and concentration on various process response like the material removal rate and grinding forces is essential to generate the technological data for EDDG This would also facilitate for optimization of the process.
- The discharge energy is an important parameter which considerably influences the wheel topography while electrodischarge dressing. Therefore, the effect of discharge energy on the wheel topography could be further investigated.

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